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Anomalous conical di-jet correlations in pQCD vs AdS/CFT

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ABSTRACT

We propose an identified heavy quark jet observable to discriminate between weakly coupled pQCD and strongly coupled AdS/CFT models of quark–gluon plasma dynamics in ultra-relativistic nuclear collisions at RHIC and LHC energies. These models are shown to predict qualitatively different associated hadron correlations with respect to tagged heavy quark jets. While both models feature similar far zone Mach and diffusion wakes, the far zone stress features are shown to be too weak to survive thermal broadening at hadron freeze-out. However, these models differ significantly in a near zone "Neck" region where strong chromo-fields sourced by the heavy quark jet couple to the polarizable plasma. Conical associated correlations, if any, are shown to be dominated by the jet induced transverse flow in the Neck zone and unrelated to the weak far zone wakes. Unlike in AdS/CFT, we show that the induced transverse flow in the Neck zone is too weak in pQCD to produce conical correlations after Cooper–Frye freeze-out. The observation of conical correlations violating Mach's law would favor the strongly-coupled AdS/CFT string drag dynamics, while their absence would favor weakly-coupled pQCD-based chromo-hydrodynamics.

1. Introduction

Recent interest in Mach-like conical di-jet correlations [1] is due to suggestions [2,3] that a measurement of the dependence of the cone angle on the supersonic jet velocity v could provide via Mach's law ($\cos\phi_M = c_s/v$) a constraint on the average speed of sound in the strongly coupled Quark–Gluon Plasma (sQGP) [4] created at the Relativistic Heavy Ion Collider (RHIC). In Ref. [5] we explored the robustness of this interpretation using the string drag model of strongly coupled plasma-field interactions [6,7] in the context of the Anti-de Sitter/Conformal Field Theory (AdS/CFT) correspondence [8]. This AdS/CFT motivated model provides a detailed holographic description of the induced stress tensor [9] in the wake of a heavy quark jet moving at a constant velocity through a static strongly-coupled $\mathcal{N}=4$ Supersymmetric Yang–Mills (SYM) background plasma at finite temperature T_0. Direct tests of this AdS/CFT string drag model using the ratio of bottom to charm nuclear modification factors in high energy nuclear collisions at RHIC and LHC have been proposed in Ref. [10]. In this work, we concentrate on another observable: the hadron correlations associated with tagged identified heavy quark jets.

The AdS/CFT stress solution for a supersonic heavy quark [7,11] features the expected far zone Mach cone as well as a strong forward moving diffusion wake. The far zone response is well described in the strong coupling limit of an $\mathcal{N}=4$ SYM plasma by a "minimal" shear viscosity over entropy density ratio $\eta/s = 1/4\pi$ [12] (near the uncertainty principle limit [13]). However, in [7,14] it was noted that the strong forward diffusion wake in the far zone of the AdS/CFT solution could spoil the double-shoulder signature of the Mach wake in accord with the general discussion of far zone hydrodynamics in [3].

In [5] it was shown that in the strict supergravity limit, $N_c \gg 1$, $g^2_{\mathrm{SYM}} \ll 1$ but $\lambda = g^2_{\mathrm{SYM}} N_c \gg 1$, in fact the far zone wakes have such small amplitudes that they only lead to a single broad peak in the away-side hadronic correlation after Cooper–Frye (CF) freeze-out of the fluid [15]. However, the AdS/CFT string drag solution features a novel non-equilibrium "Neck" near zone, where especially strong transverse flow relative to the jet axis induces an apparent conical azimuthal correlation of associated hadrons even after CF thermal broadening at freeze-out.

In Ref. [5], the Neck zone was defined as the region near the heavy quark where the local Knudsen number [16] is $K_N(X) = \Gamma_s|\nabla\cdot\mathbf{M}|/|\mathbf{M}| > 1/3$. where $M^i(X) = T^{0i}(X)$ is the momentum flow field of matter and $\Gamma_s \equiv 4\eta/(3sT_0) \geqslant 1/(3\pi T_0)$ is the sound attenuation length, which is bounded from below for ultra-relativistic systems [12,13]. In the Neck region the induced transverse flow is surprisingly large and is unrelated to the far zone Mach's law. In

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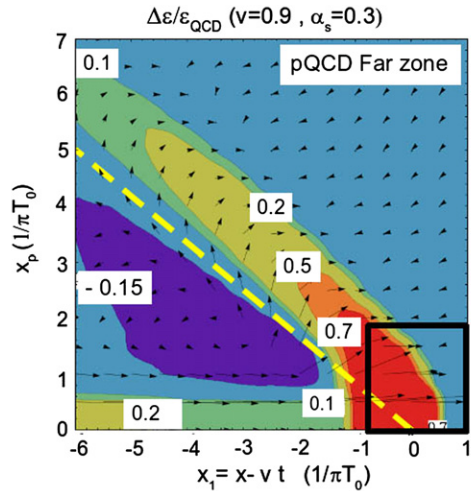

Fig. 1. (Color online.) The fractional energy density perturbation $\Delta\varepsilon/\varepsilon_0 \equiv \varepsilon(x_1, x_p)/\varepsilon_0 - 1$ (in the lab frame) due to a heavy quark with $v = 0.9$ in a QCD plasma of temperature $T_0 = 200$ MeV. The induced fluid stress was calculated using $(3+1)$D hydrodynamics [25] with the anomalous pQCD source of Neufeld [20] (left panel) and AdS/CFT [5] (right panel). A trigger jet (not shown) moves in the $-\hat{x}$ direction. The away-side jet moves in $\hat{x}$ direction and contours of $\Delta\varepsilon/\varepsilon_0 = -0.15, 0.1, 0.2, 0.5, 0.7$ are labeled in a comoving coordinate system with $x_1 = x - vt$ and the transverse radial coordinate x_p in units of $1/\pi T_0 \approx 0.3$ fm after a total transit time $t = 5$ fm/$c = 14.4/(\pi T_0)$. The ideal Mach cone for a point source is indicated by the yellow dashed line in the x_1–x_p plane. See Fig. 2 for a zoom of the Neck region inside of the black box.

AdS/CFT, this is the field-plasma coupling zone where the stress tensor has a characteristic interference form dependence on the coordinates, $O(\sqrt{\lambda}T_0^2/R^2)$ [17,18], with R denoting the distance to the heavy quark in its rest frame. In contrast, the stress in the far zone has the characteristic $O(T_0^4)$ form. In addition, very near the quark the self Coulomb field of the heavy quark contributes with a singular stress $O(\sqrt{\lambda}/R^4)$ [9].

The above strong coupling AdS/CFT results motivated us in the present work to study whether similar novel near zone field-plasma dynamical coupling effects arise in weakly coupled perturbative Quantum Chromodynamics (pQCD). In Refs. [19–21] the heavy quark jet induced stress in a weakly-coupled QGP (wQGP in contrast to sQGP) was computed analytically in the linear response approximation based on the Asakawa–Bass–Müller (ABM) [22,23] generalization of chromo-viscous hydrodynamics [24]. The ABM generalization concentrates on the "anomalous diffusion" limit, where the conductivity is dominated by field rather than stochastic dissipative scattering dynamics.

As in the AdS/CFT string drag model, the generic far zone Mach and diffusion wakes are also clearly predicted in the pQCD based ABM formulation [19,21] as we show for the case of a $v = 0.9$ heavy quark jet in Fig. 1. However, the question of whether the far zone Mach cone flow correlations survives CF freeze-out of the plasma was not addressed up to now. In this Letter, we extend the work of [19,21] by solving numerically the full nonlinear $(3+1)$D relativistic hydrodynamic equations using the SHASTA hydro code [25], supplemented with the chromo-viscous stress source derived in Refs. [19,20]. We specialize to the ideal fluid case of vanishing viscosity to minimize the dissipative broadening of any conical correlations and therefore maximizing the signal to noise ratio.

We emphasize that our aim here is not to address the current light quark/gluon jet RHIC correlation data. Our goal is to point out the significant differences between weakly coupled and strongly coupled models mechanisms of heavy quark energy loss that can be tested experimental when identified heavy quark (especially bottom quark) jet correlations will become feasible to measure. We limit this study to the most favorable idealized conditions (uniform static plasma coupled to the external Lorentz contracted color fields). Common distortion effects due to evolution in finite expanding plasma geometries will be reported elsewhere.

We use natural units below and Lorentz indices are denoted with Greek letters $\mu, \nu = 0, \ldots, 3$ while internal $SU(N_c)$ adjoint color indices are $a = 1, \ldots, N_c^2 - 1$. Also, the Minkowski metric $g_{\mu\nu} = \text{diag}(-,+,+,+)$ is employed. In our system of coordinates, the beam is in the z direction, the associated heavy quark jet moves along the x direction with velocity $\mathbf{v} = v\hat{x}$. We define $x_1 = x - vt$ and x_p is the transverse cylindrical radial coordinate perpendicular to the jet axis.

2. Stress zones

Energetic back-to-back jets produced in the early stages of a heavy ion collision transverse to the beam axis traverse the sQGP and deposit energy and momentum along their path in a way that depends on the non-equilibrium details of the physics of the field-plasma coupling. In the case when one of the jets is produced near the surface (the trigger jet), the other supersonic away-side jet moves through the plasma and generates in the far zone a Mach like conical perturbation in the plasma stress as seen in Fig. 1. The resulting conical correlation (with respect to the away-side jet axis) is naturally expected to lead to an enhancement of associated hadrons at the characteristic Mach angle [2,3]. Below some transverse momentum saturation scale [28,29], jet physics depends on the properties of the medium and one can test different models of jet-medium coupling dynamics by studying the detailed angular and rapidity correlations. In this work we demonstrate a striking difference between strongly coupled AdS/CFT and moderate coupling, multiple collision pQCD transport models for that coupling, and study their experimentally measurable consequences.

We ignore here the near-side associated correlations and focus on away-side jet-hadron azimuthal correlations. The energy–momentum stress induced by the away-side heavy quark jet in both pQCD and AdS/CFT can be conveniently decomposed into four separate contributions as in [5]

$$T^{\mu\nu}(X) = T^{\mu\nu}_{\text{bg}} + \delta T^{\mu\nu}_{\text{Mach}}(X) + \delta T^{\mu\nu}_{\text{Neck}}(X) + \delta T^{\mu\nu}_{\text{Coul}}(X). \tag{1}$$

The static isotropic background stress tensor is assumed to be $T^{\mu\nu}_{\text{bg}} = \text{diag}(\varepsilon, p, p, p)$, where $\varepsilon = KT_0^4$ is the corresponding background energy density of a gas of massless $SU(3)$ gluons $K_{\text{QCD}} = 8\pi^2/15$ whereas for $SU(N_c)$ SYM $K_{\text{SYM}} = 3\pi^2(N_c^2 - 1)/8$. In both cases, $\varepsilon = 3p$ and the background temperature is T_0.

The Coulomb contribution to the energy–momentum tensor $\delta T^{\mu\nu}_{\text{Coul}}(X)$ arises from the near zone Lorentz contracted Coulomb field that remains attached to the heavy quark since we consider only moderate but supersonic velocities $c_s \leqslant v \leqslant 0.9$. We can therefore neglect radiative energy loss that dominate in the ultrarelativistic case. The bare comoving Coulomb self-field stress has the singular form $\delta T^{\mu\nu}_{\text{Coul}} \propto 1/R^4$ in the quark rest frame. In both pQCD and AdS/CFT cases we subtract this vacuum self-field stress as in [7]. In other words, the zero temperature contribution to the in-medium stress tensor is always subtracted. While in AdS/CFT the form of the Coulomb tensor is known exactly [9], in pQCD this contribution can only be calculated perturbatively. The leading order expression for the chromo-fields produced by the source in pQCD, in the limit where the dielectric functions are set to unity, displays the same Lienard–Wiechert behavior as in AdS/CFT.

The far zone "Mach" part of the stress can be expressed in terms of the local temperature $T(X)$ and fluid flow velocity fields $U^\alpha(X)$ through the first-order Navier–Stokes stress form